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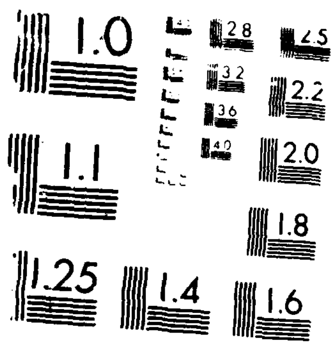
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ANNUAL REPORT

ELECTRIC FIELDS IN EARTH ORBITAL SPACE

Magnetospheric Structural Dynamic Response to External Variables

November 1987

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McDonnell Douglas Astronautics Company

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MCDONNELL DOUGLAS CORPORATION

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Magnetospheric Structural Dynamic Response to External Variables

November 1987 N00014-80-C-0796

Prepared by

W. P. Olson
K. A. Pfitzer

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-HUNTINGTON BEACH
5301 Bolsa Avenue Huntington Beach, California 92647 (714) 896-3311

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It is known that the magnetosphere responds dynamically to changes in the interplanetary magnetic field (IMF). Instead of the qualitative reconnection theory (which we believe is basically incorrect), we have examined this response in terms of electromagnetic wave propagation in the interplanetary region. We suggest that the interplanetary plasma (solar wind) is magnetized by the solar magnetic sector structure. Electromagnetic waves of high frequency can propagate through the solar wind without appreciable attenuation. It is the interaction of these disturbance waves with the magnetosphere that causes the observed magnetospheric response to the IMF. We have examined quantitatively the propagation of electromagnetic disturbances in the interplanetary region and their interaction with the magnetosphere. Only certain modes propagate and there are further restrictions on the waves at the magnetopause. We have shown that a southward turning wave enters the tail of the magnetosphere and weakens the magnetic field in the plasma sheet. A northward turning wave increases the field. In this report we present the implications of these waves on substorm dynamics.

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1.0 INTRODUCTION AND BACKGROUND

Our magnetospheric work At MDAC over the past few years has centered on understanding physically the mechanism for the transfer of energy, mass, and momentum from the magnetosheath region into the magnetosphere, and on describing the interaction of the interplanetary magnetic field (IMF) with the magnetosphere. These are basic problems in magnetospheric physics since these processes must be understood before quantitative models of the many observed magnetospheric processes can be constructed. These models are required for the prediction and specification of near earth orbital environmental "weather" parameters such as: trapped radiation fluxes, upper atmospheric density, ionospheric electron density, auroral particle precipitation and associated auroral luminosity, etc.

The question of particle entry into the magnetosphere has been one of the most fundamental problems in magnetospheric physics since it became an issue in the early 1960s. During the "correlative phase" of magnetospheric physics in the 1970s this question became even more basic to our understanding of the magnetosphere since there was growing correlative evidence that the magnetosphere was under the control of the solar wind and interplanetary magnetic field. The magnetospheric substorm was (and continues to be) of particular interest since the basic substorm question concerns whether or not the tail of the magnetosphere is controlled by the solar wind and interplanetary magnetic field or whether the plasmas in the tail can store energy and suddenly release it (a substorm) without external influences.

We have developed quantitative models of particle entry and solar wind and IMF influence on the magnetosphere. During the past year, our attention has been focused on the primary question: Is the substorm controlled by forces external to the magnetosphere or is it primarily a manifestation of processes occurring within the magnetospheric tail region?

Our models are driven by solar wind and IMF parameters. All parts of the models have been developed from first principles. It is our hope that in addition to shedding light on the substorm problem, the models will become useful in the truly predictive sense: that they can be used to anticipate the behavior of several of the routinely observed magnetospheric features and their subsequent effects on the upper atmosphere and ionosphere and the orbital systems that operate in that region.

The solar wind "entry" problem and the substorm have both been important problems in magnetospheric physics since the 1960s. Currently, both problems are explained primarily in terms of "reconnection theory", which we believe has major flaws. We discuss the entry problem first.

1.1 Solar Wind Entry into the Magnetosphere

The first magnetospheric problem to be considered theoretically was the calculation of the size and shape of the magnetosphere. They were determined by equating the solar wind pressure with the energy density (pressure) of the magnetospheric magnetic field. To make this three dimensional problem tractable, an assumption was made; that the solar wind particles were all specularly (mirror like) reflected off of the geomagnetic field, $\underline{B}$. This approximation to the real field was quite reasonable since the interaction region of the incident particles with $\underline{B}$ is very small (10s to 100s of km) compared to the scale size of the magnetospheric magnetic field (10s of thousands of km). This "pressure balance" formalism was used by many investigators to successfully determine the shape and size of the magnetosphere. The unfortunate legacy of this work, however, was the assumption that all of the solar wind particles are reflected off of the geomagnetic field and that none enters the magnetosphere.

Therefore, as early as 1960, concepts were already being suggested for the transfer of momentum across the boundary between interplanetary space (or more precisely, the magnetosheath) and the magnetosphere (the "viscous interaction" theories). Later, as the influence of the IMF on the magnetosphere became well established, the early work of Dungey and others on "reconnection" was suggested as another means for providing energy and mass to the magnetosphere from the solar wind. Several other concepts have been suggested: plasma instabilities along the magnetopause, a structured or "gusty" solar wind, and various diffusion processes.

All this time the assumption that solar wind particles were specularly reflected at the magnetopause was left basically unchallenged. Yet, it was well known that the higher energy solar cosmic rays readily gain access to the magnetosphere. Their entry was explained (correctly) by suggesting that since such particles have relatively large gyroradii, their interaction region with $\underline{B}$ is large enough for them to sample the structure of $\underline{B}$ and therefore possibly gain access to the magnetosphere. (Recall that the path of a charged particle moving in a uniform magnetic field is circular. This fact forms the basis for the specular reflection assumption.)

However, it is known that the strength of $\underline{B}$ along the magnetopause varies from about 75 nT at the nose of the magnetosphere to less than 5 nT in the distant magnetotail. Thus there is a gradient (structure) in $\underline{B}$ (although it is admittedly small over a distance comparable to the gyroradius of a solar wind proton). It was reasonable then to ask: What is the lowest energy particle to gain access to the magnetosphere because of the existence of this known (small) gradient in $\underline{B}$?

We have examined that question in quantitative detail and found that as the energy of the incident particle decreases, the range of directions through which it can enter the magnetosphere also decreases but that even for particles with solar wind energies the solid angle of allowed directions of incidence is finite. Thus, we have concluded that: The assumption of specular reflection may reasonably be used in the determination of magnetospheric size and shape but that some solar wind particles routinely gain access to the magnetosphere.

This work has suggested to us that all the diffusion and plasma instability theories may not be necessary in order to explain the interaction of the magnetosphere and solar wind; that instead all that was necessary was a more realistic examination of the interaction of the solar wind particles with $\underline{B}$.

We have been encouraged by this work since qualitatively it suggests that the solar wind particles will enter the magnetosphere along the sides of the tail and in the dayside cusp regions (where they are required). This contrasts with reconnection theory which suggests that particle entry is primarily at the nose of the magnetopause and over the lobes of the tail. Thus the reconnection theory requires the presence of a complex electric field structure within the magnetosphere in order to allow the entering particles to drift across $\underline{B}$ to the regions where they are observed.

1.2 Problems with the Reconnection Theory

Another basic problem in magnetospheric physics is the understanding of the interaction of the IMF with the magnetosphere. Currently, most of the magnetospheric physics community chooses to represent this interaction in terms of reconnection theory. Basically, reconnection theory supposes that the two magnetic field sources (the IMF and $\underline{B}$) become "tied together" in the presence of a plasma. This process has the consequence of connecting the two magnetic fields such that field lines emanating from one are ultimately joined to the other source. An important by-product is the acceleration of charged particles in the "reconnection region". Proponents of reconnection theory suggest that it can explain the entry of the required solar wind plasma into the magnetosphere and also the relatively hot plasma observed in the tail of the magnetosphere.

We have several problems with this theory, however, and with support from ONR have developed an alternative physical description of the IMF and its interaction with the magnetosphere. Some of the problems we see in reconnection theory are as follows. Reconnection is dependent on the direction of the IMF which is observed to change, typically on the order of every few hours. Thus it is not clear to us how any reconnection process can drive any of the processes observed to persist at all times in the magnetosphere (e.g., the plasma sheet, the several magnetospheric currents, etc.). Its proponents state that reconnection takes place predominantly at the nose of the magnetopause and over the lobes of the tail. This poses the requirement of maintaining a complex electrostatic field at all times but in varying directions in order to permit particles entering there to journey to those regions where they are required (e.g., the plasma sheet). Finally, there is no conclusive evidence that this process operates in the IMF and magnetosphere even though a concerted effort has been expended searching for examples. A case in point was the AMPTE ion releases made upstream of the bow shock. No evidence was found for the presence of any ions entering near the nose of the magnetosphere even though the releases were performed during intervals of southward IMF (conditions favorable for dayside reconnection).

2.0 THE MAGNETOSPHERIC SUBSTORM

The substorm problem has been observed for over two decades. The magnetospheric substorm manifests itself primarily in terms of changes observed in the tail of the magnetosphere. However, there are also auroral, ionospheric, and surface magnetic field changes associated with the substorm.

In the tail of the magnetosphere, the magnetic field and the size and density of the plasma sheet change dramatically during the substorm. There has been intense activity directed at correlating the changes in the tail during substorm activity with variability in solar wind and IMF parameters. These have met with limited success. It is clear that there is some correlation but none of these correlative studies suggest that there is a clean cause and effect relation that awaits understanding. However, the controversy continues with one school saying that the substorm is primarily the manifestation of the magnetospheric tail "doing its thing" and another suggesting that perhaps this process primarily occurs under the control of the solar wind and IMF.

We have developed tools to deal with the substorm problem and to examine it in a quantitative and global fashion. We are confident that our current work will lead to the development of better quantitative models of gross magnetospheric features and a capability for <u>predicting</u> magnetospheric behavior.

3.0 RECENT ACTIVITIES

We have recently worked on the entry of solar wind into the magnetosphere and on the control the interplanetary magnetic field (IMF) has on the magnetosphere. Correlative data conclusively prove that both the solar wind and the IMF exert considerable influence on magnetospheric processes, and the magnetospheric substorm in particular.

Our work on this subject may be roughly divided into two parts, particle entry and representation of the interaction of the IMF with the magnetosphere. We discuss particle entry first.

3.1 Particle entry

We have quantitatively determined where on the magnetopause that low energy (solar wind) charged particles can gain entry to the magnetosphere. To do this, we used a realistic quantitative model of the magnetospheric magnetic field. Particles of the same energy but differing incidence angles where then introduced to this field at a point on the magnetopause. It was found that at most points a finite "entry cone" persists. The entry cone is defined as that region (represented as a solid angle) through which particles have access to the magnetosphere. The value of the entry cone varies with particle energy and location on the magnetopause. We found that the entry cone was largest along the equatorial flanks of the tail. (An example of the entry cone is shown in Figure 1 and the size of the entry cone over the flanks of the tail is shown for protons in Figure 2.) The entry cone is exactly zero along the intersection of the noon-midnight meridian with the magnetopause by symmetry since there the particles really are specularly reflected.

Study of entry cone size suggests that no magnetosheath particles enter the magnetosphere over the lobes of the tail and also that no particles enter at the nose of the magnetosphere. The regions where entry does readily occur are along the sides (flanks) of the tail and in the vicinity of the dayside cusps. The "gradient drift" entry mechanism therefore supplies solar wind plasma directly to those regions of the magnetosphere where plasmas are observed (e.g., the plasma sheet in the tail and the dayside cusps). This is unlike the reconnection theories which introduce plasma near the nose of the

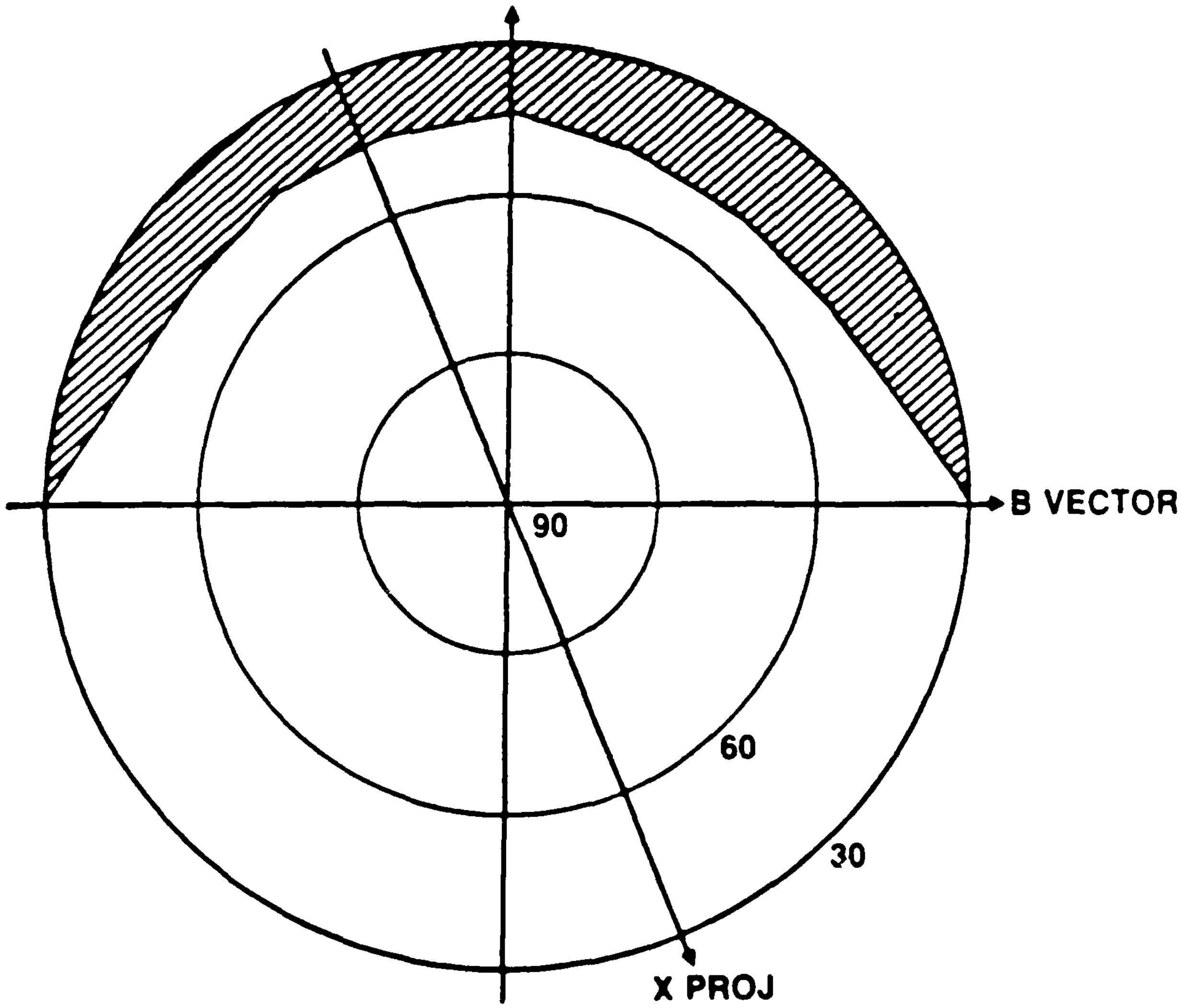

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Figure 1. Description of an entry cone. The shaded portion represents the range of impact directions over which the particle gains entry to the magnetosphere. The boundary location is down the tail just above the magnetic equatorial plane (along the dawn flank). The projection of the x axis (in solar magnetospheric coordinates) and the direction of B at the opint are shown. Particles moving away from the sun with near grazing incidence are shown as "allowed" impact angles.

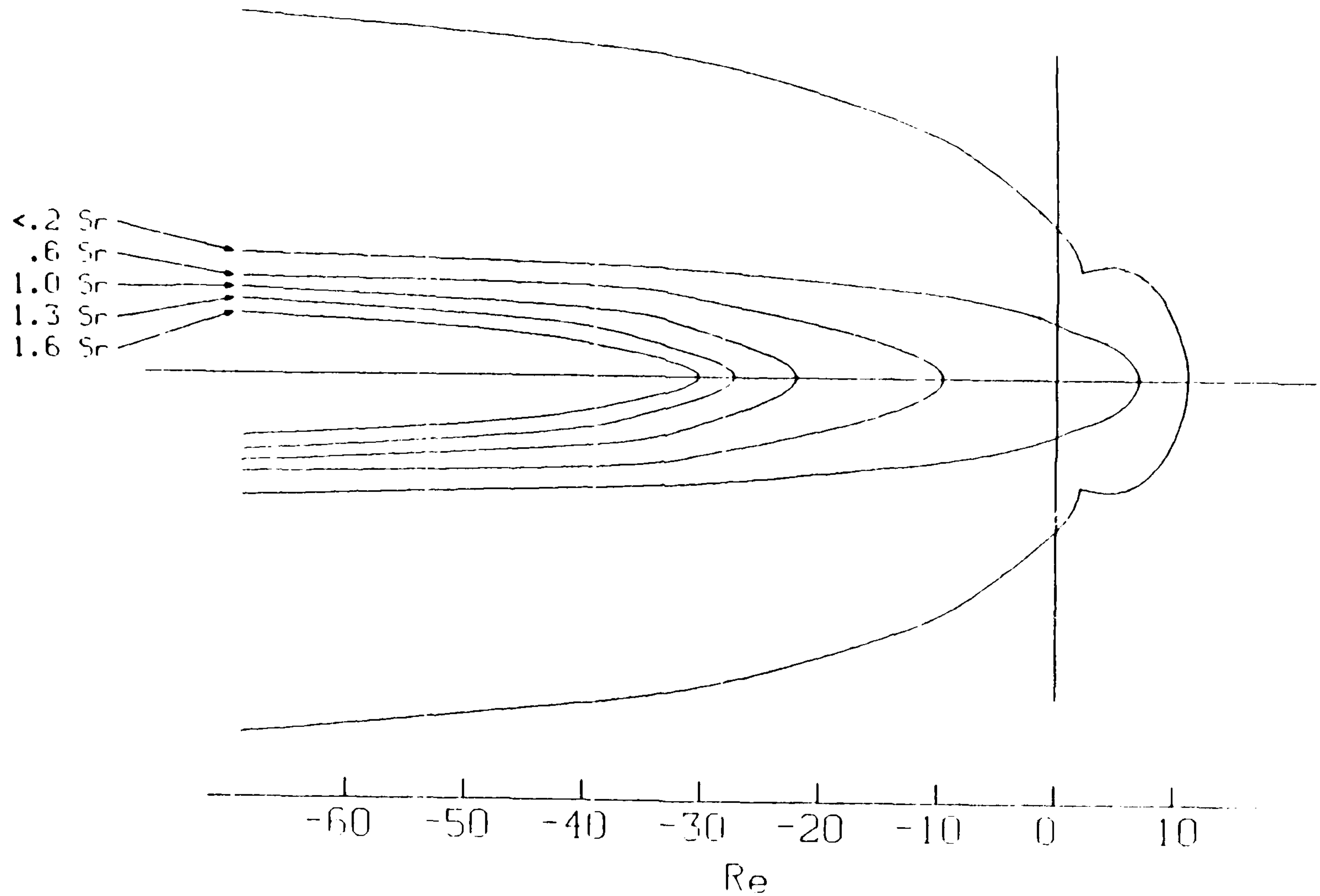

Figure 2. Contours of constant entry cone magnitude on the dawn side of the magnetosphere

magnetosphere and over the lobes of the tail. To date this work on particle entry has shown that particle entry depends on the strength of B, its structure, and on the particle distribution function.

3.2 Representation of the Interplanetary Magnetic Field (IMF)

Correlative data establish beyond doubt that the IMF exerts considerable influence on magnetospheric processes. This subject has been exhaustively studied in terms of reconnection theory. We, however, have several complaints with reconnection theory (it introduces particles into the wrong regions of the magnetosphere: the IMF [and therefore the reconnection process] is continuously changing direction; there is little or no direct magnetospheric observational evidence for its existence etc.); and have, therefore, attempted to explain the interaction of the IMF with the magnetosphere in a way that we can understand the physics.

Basically, we have represented the IMF as the superposition of electromagnetic waves. The only limitation of our investigation is that we must restrict it to wavelengths that are small with respect to the scale size of the magnetosphere. Thus we can examine only waves (or disturbances) with periods less than one hour. Although limited in this regard, our study sheds light on many aspects of the interaction of the IMF with the magnetosphere. These are briefly reviewed. We first summarize our findings on the propagation of electromagnetic disturbances in the solar wind.

The interplanetary field (represented as the superposition of several periodic electromagnetic waves) can persist only in the presence of the solar wind plasma. In the absence of a plasma, the presence of a time varying magnetic field in interplanetary space of the magnitude of only a few nT would have associated with it an electric field with a magnitude on the order of 1 volt per meter, which is at least three orders of magnitude larger than the magnitude of electric fields observed in the interplanetary region.

In the solar wind, in the absence of a background ambient magnetic field, any disturbances with periods on the order of minutes to hours will be rapidly attenuated unless they are driven continuously in a local region. Electromagnetic disturbances in the solar wind can persist only in the presence of an ambient (lower frequency) magnetic field. When such conditions are present (the presence of both plasma and "background" magnetic field) electromagnetic waves with periods from a few minutes to several hours can propagate over distances large with respect to the magnetosphere size without appreciable attenuation. The background (ambient) magnetic field is provided by the "solar sector magnetic field" which is co-produced with the solar wind. It moves outward from the sun with the solar wind, and has a period of about two weeks - much longer than the characteristic periods of the electromagnetic disturbances being considered. Electromagnetic waves allowed in the interplanetary medium propagate at the Alfven speed. There are two wave modes that propagate without appreciable attenuation.

1. When the propagation vector is parallel to the ambient magnetic field.

2. When both the propagation vector and the disturbance electric field are perpendicular to the ambient magnetic field direction.

Each of these cases is represented schematically in Figure 3.

It then was a simple exercize to examine the interaction of such waves when they encountered a discontinuity in plasma (the magnetopause). At the magnetopause these electromagnetic disturbances are reflected and refracted. A portion of the field can penetrate the magnetosphere. The properties of the penetrating field are determined by magnetospheric parameters (e.g. plasma density, "ambient" magnetospheric magnetic field, etc.). Penetration of these interplanetary magnetic disturbances into the magnetosphere occurs most readily where the magnetic field strength is low and the plasma density relatively high. Thus, the flanks of the tail are the primary region for IMF penetration into the magnetosphere. An example of allowed transmission is shown in Figure 4 where B_0 represents the ambient fields in the magnetospheric and interplanetary regions and B' and E' define the disturbance. Note that the directions of B' and E' do not immediately change as the disturbance enters the magnetosphere and that E' is always perpendicular to B_0.

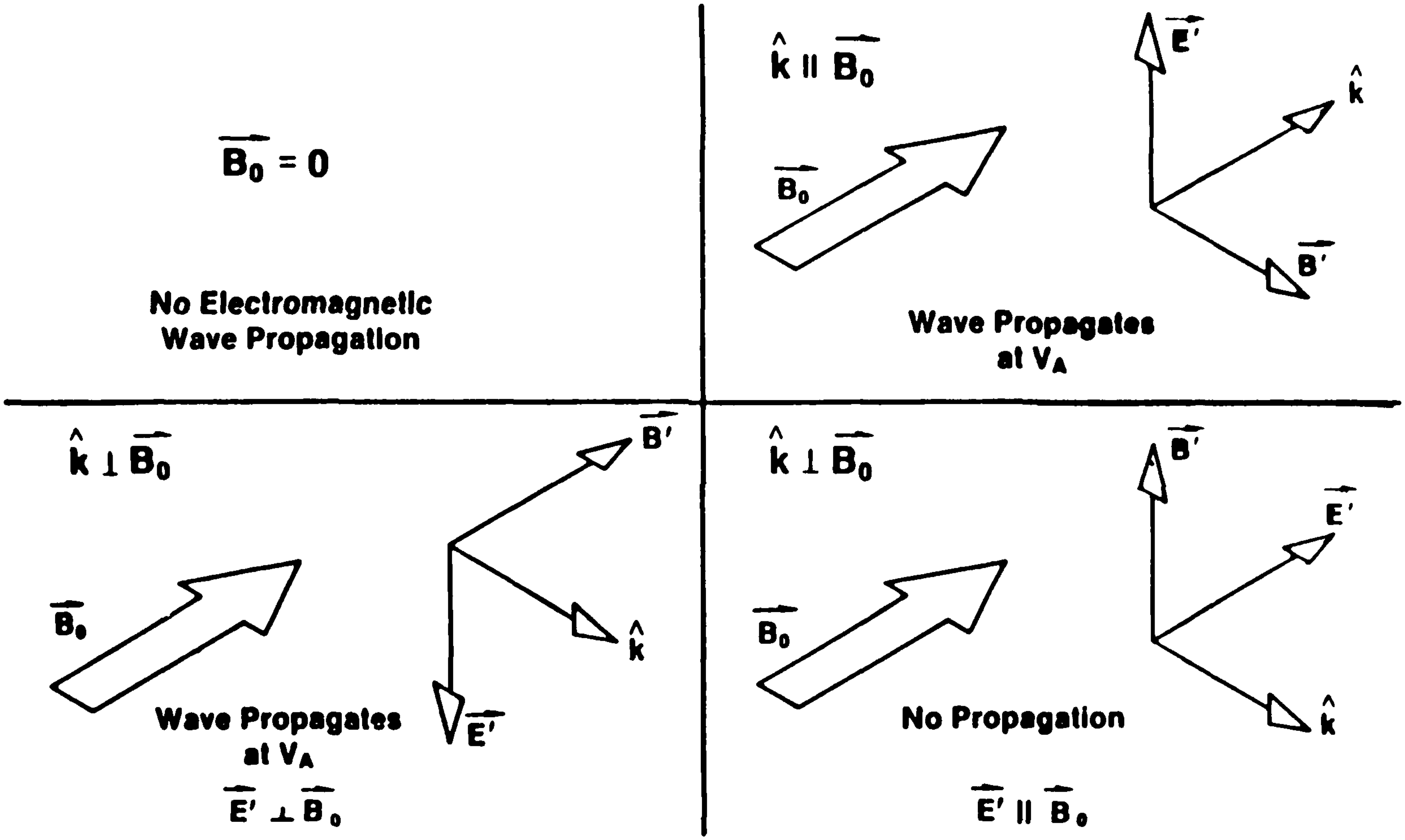

Figure 3. Electromagnetic wave propagation in a tenuous plasma. The wave propagates with little attenuation when its propagation vector is parallel to the direction of the ambient magnetic field, and when the propagation vector and the disturbance E vector are perpendicular to B.

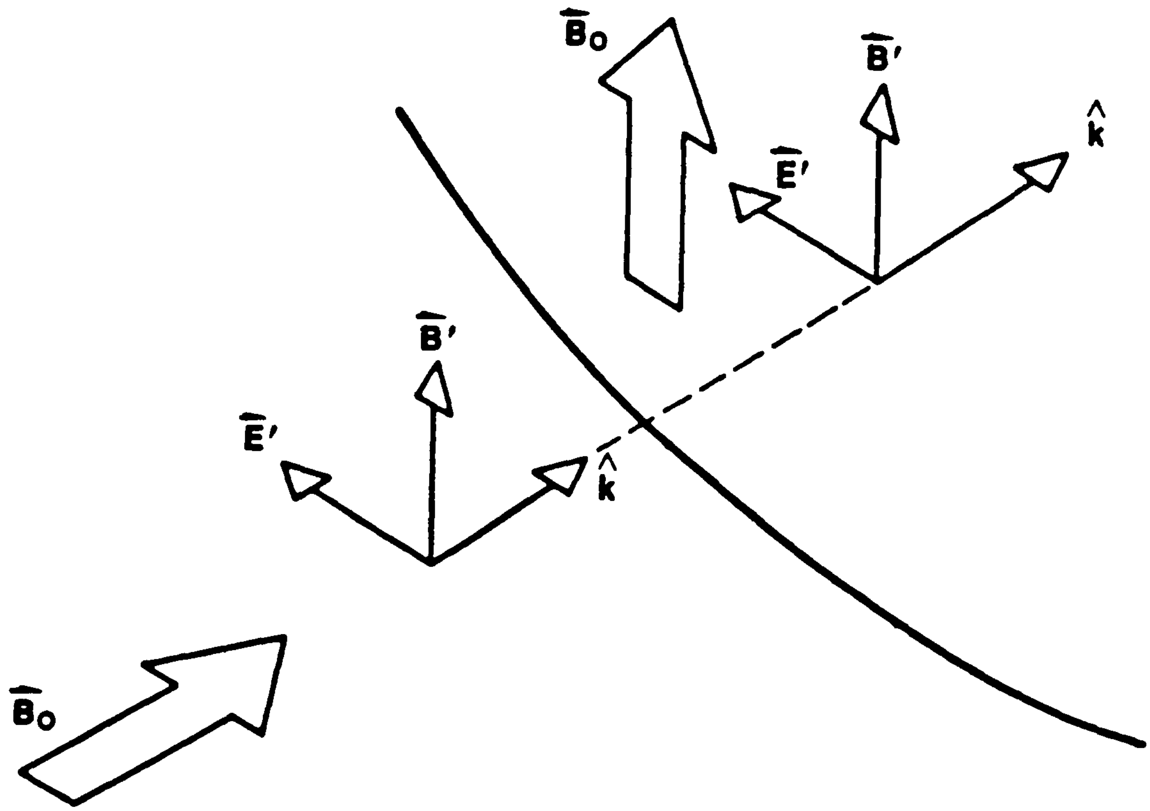

Figure 4. Transmission through the magnetopause and propagation in the magnetosphere. This process is completely analogous to the passage of light from vacuum into glass. In both media (the interplanetary region and in the magnetosphere) the disturbance E vector must be perpendicular to the ambient magnetic field direction.

Magnetic disturbances in the north or south direction (perpendicular to the magnetic equatorial plane and parallel or antiparallel to the ambient magnetospheric field resident there) can most significantly influence the tail plasma sheet region. The entry of a northward disturbance field decreases the beta (ratio of particle kinetic energy to magnetic field energy density) while a southward field increases beta. We note that for a given ambient magnetospheric field, the entry of a southward disturbance field has more effect than that of a northward disturbance of the same magnitude on the percent change in beta. Thus this work on a physical representation of the IMF has already suggested why a southward directed IMF is observed to have such a large influence on the magnetospheric substorm process.

4.0 MAGNETOSPHERIC RESPONSE TO EXTERNAL VARIABLES

The basic problem of magnetospheric physics remains the explanation of the response of the magnetosphere to variations in the solar wind and the IMF. The work that has been completed as well as the work already in progress places us in a position to take a large step toward the goal of solving that problem. We now understand how the solar wind enters (and influences) the magnetosphere. We have also developed a physical description for the interaction of the IMF (represented as the superposition of a set of periodic electromagnetic disturbances) with the magnetosphere, and are studying the dynamics of energization processes in the magnetotail.

In the past years, we have been active participants in the Coordinated Data Analysis Workshops (CDAW) sponsored by NASA and other government agencies. For each of these workshops, we have supplied "event models". An event model is one that represents the magnetospheric magnetic field as it changes with time through the particular event. The models are based on dynamic representations of the three major current systems, the magnetopause ring and tail current systems. These models are the first step toward quantitative models that are capable of representing changes in the magnetosphere as it responds to the solar wind and the IMF. The models developed for CDAW use as input the solar wind pressure to determine the magnetopause currents and algorithms based on the D^{st} (magnetic index) and the tail lobe field strength to model changes in the ring and tail current systems. These models are remarkably accurate in predicting the response of the magnetospheric magnetic field to changes in the solar wind pressure in the dayside region of the magnetosphere.

This event model we developed for CDAW, with its separate expansions for the magnetopause, ring and tail fields, provided a useful initial model for studying the interaction of the IMF with the magnetosphere.

In our earlier work for ONR, we showed that variations in the IMF can be represented as a superposition of a set of periodic electromagnetic disturbances propagating in the magnetized interplanetary plasma, the solar wind. The solar wind is represented as a tenuous plasma with an imbedded magnetic field, the well known solar sector structure magnetic field. Higher frequency waves can propagate in this medium with the Alfven speed if their propagation direction is parallel to the sector structure magnetic field. Such waves can also propagate if the propagation vector is perpendicular to the sector structure magnetic field providing the wave's electric field. The study also determined that when the wave interacts with the magnetopause, the wave is either reflected or transmitted. The study determined that transmission was possible only near the equatorial flanks of the tail and near the cusp regions, regions of weak magnetic field and where the plasma density inside the magnetopause was relatively high. Once the wave has penetrated through the boundary of the magnetospher, it will either travel at the local Alfven speed or be absorbed. It was determined that only waves whose magnetic field vector oscillates in the north/south direction are capable of propagating in the interplanetary medium, pass through the boundary near the equatorial flanks and then propagate within the magnetospheric tail field region.

5.0 SUMMARY OF WORK PERFORMED IN PAST YEAR

Variations in the north south component of the interplanetary field have long been associated with substorm triggers. To begin the study of substorm trigger, studies of the magnetic field variations in the magnetospheric tail in response to changes in the IMF were initiated. The dynamic magnetic field model with nominal solar wind condition was used as the initial condition for this study. Figure 5 shows a noon-midnight meridian plot of the field lines for the nominal undisturbed magnetosphere. A north-south wave of arbitrary amplitude traveling along the interplanetary sector magnetic field vector was allowed to interact with the equatorial flanks of the tail (see Figure 4). The transmission/refraction of the wave was determined using the equations developed in last year's effort. Once inside the boundary, the wave was allowed to propagate in the equatorial plane at its initial direction. This unchanging propagation direction is approximated since the plasma density and the magnetic field strength within the tail are not constant. Variations in the index of refraction of the medium slowly change the direction of the wave. However, a uniform propagation direction is a reasonable first approximation that greatly simplifies the problem.

When the IMF changes to a northward direction, the wave increases the tail field strength within the plasma sheet. The enhanced magnetic field within the plasma sheet has three distinct signatures. These are:

The tail field becomes more dipolar. As the northward pointing variation moves down the tail and from dawn to dusk and in the anti-sun direction, the B_z component in the plasma sheet increases and more field lines are observed to thread through the plasma sheet. This reduces the size of the polar cap and increases the thickness of the plasma sheet. Polar cap size reduction should first be noticed near 3 UT.

Since the B_z component of the magnetic field is enhanced, the magnetic limiting current in the plasma sheet is increased (Olson and Olson, 1986). That is, we expect an increase in the particle population within the plasma sheet.

Increases in the magnetic field cause dB/dt variations. For the northward change in the IMF, dB/dt changes are positive and thus particle energization will occur.

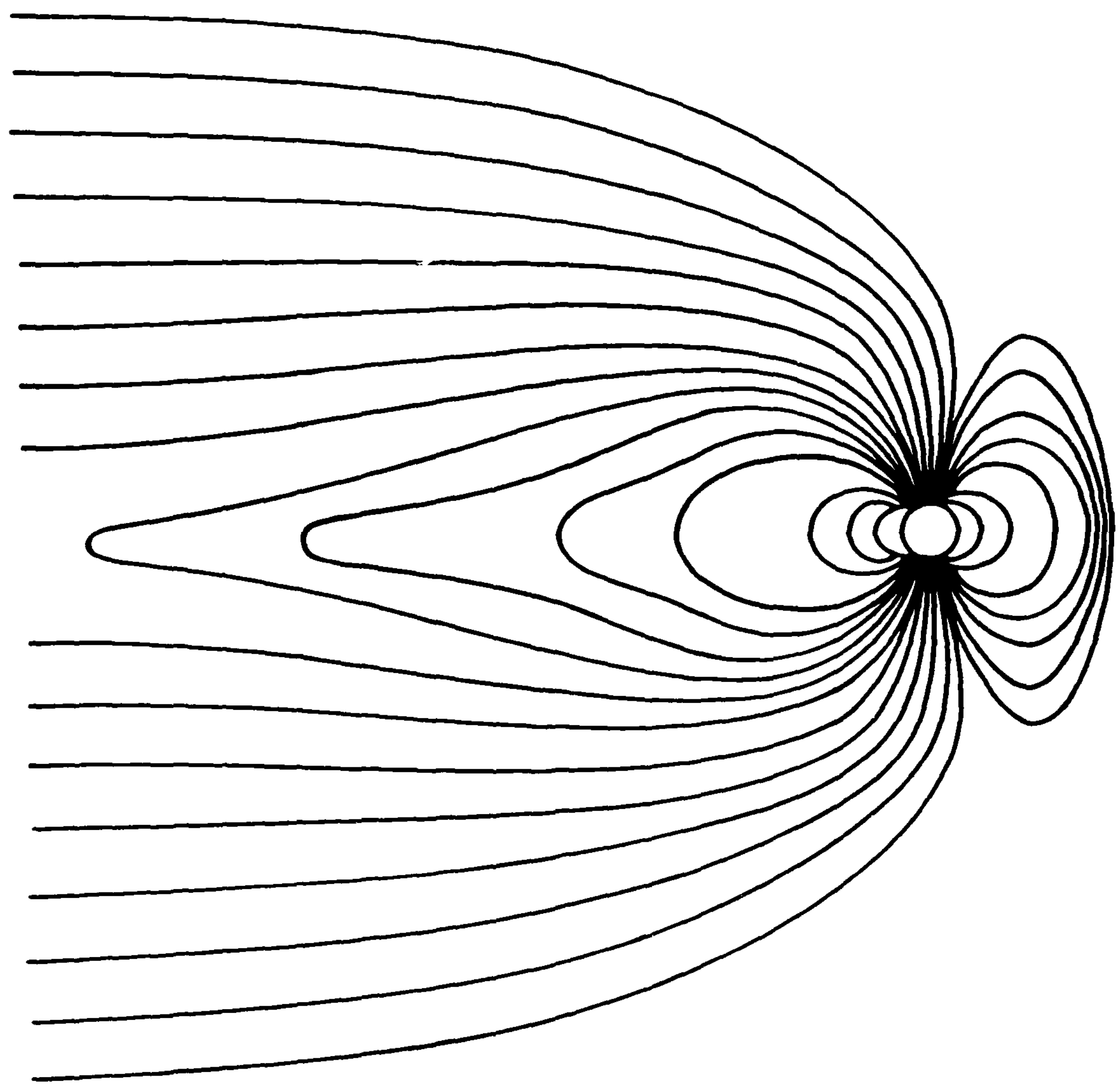

Figure 5. Field lines in the noon-midnight meridian plane during quiet times.

Southward changes have the opposite effect and are even more pronounced since then the total magnetic field can be made very small. A south pointing wave entering on the dawn equatorial flank causes a reduction in the magnetic field in the plasma sheet. This causes the following effects:

The tail becomes more tail-like. The B_z component in the plasma sheet is reduced. The reduction spreads from dawn to dusk and anti-sunward. The size of the polar cap will grow and the plasma sheet will thin. Polar cap expansion should first be observed near 3 UT.

Depending on the amplitude of the southward pointing wave, a neutral line may develop in the tail field. This neutral line will form first near the dawn side and expand toward dusk and move in the anti-sun direction.

Reduction of the B_z component in the plasma sheet will reduce the magnetic limiting current and thus reduce the particle population within the plasma sheet.

These quantitative scenarios are very similar to observation at the onset and during the development of a substorm. Additional work must now be done to quantify these results. The propagation speed of the waves in the tail must be used to determine delays between the arrival of the wave at the magnetopause and the observed variations within the plasma sheet. A step by step quantitative comparison between a 'classic' substorm event and the observed response of the magnetosphere to the IMF change must now be initiated.

6.0 PRESENTATIONS AND PUBLICATIONS

Variation of Plasma Velocity Distribution Functions Across the Low-Latitude Boundary Layer Driven by the Gradient Drift Entry Process, presented to the IUGG XIXth General Assembly, 10-22 August 1987, Vancouver, BC, McDonnell Douglas Astronautics Company Paper No. H2585.

The Entry of Magnetic Waves into the Magnetosphere and their Effect on the Plasma Sheet, presented to the IUGG XIXth General Assembly, 10-22 August 1987, Vancouver, BC, McDonnell Douglas Astronautics Company Paper No. H2584.

The Topology of the Parallel Currents Flowing Into and Out Of the Ionosphere, presented to the IUGG XIXth General Assembly, 10-22 August 1987, Vancouver, BC, McDonnell Douglas Astronautics Company Paper No. H2593-I.

Magnetospheric Response to Gradient Drift Entry of Solar Wind Plasma, presented at the AGU Spring Meeting, 18-22 May, 1987, Baltimore, MD, McDonnell Douglas Astronautics Company Paper No. H2586.

Entry of Solar Wind Plasma through the Gradient Drift Entry Process, presented at the AGU 1986 Fall Meeting, Dec. 8-12, 1987, San Francisco, CA, McDonnell Douglas Astronautics Company Paper No. H2547.

Self Consistent Magnetosphere Model Controlled by Magnetic Limiting Currents, presented at the AGU 1986 Fall Meeting, Dec. 8-12, 1987, San Francisco, CA, McDonnell Douglas Astronautics Company Paper No. H2546.

A Storm Time Model of the Magnetic Field in the Inner Magnetosphere, presented at the AGU 1986 Fall Meeting, Dec. 8-12, 1987, San Francisco, CA, McDonnell Douglas Astronautics Company Paper No. H2546.

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